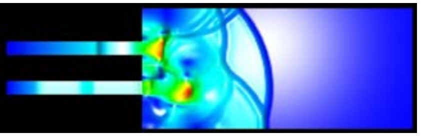
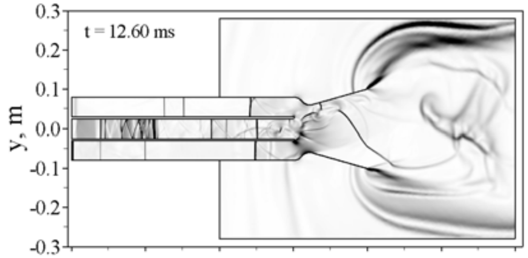
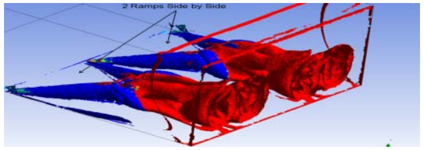


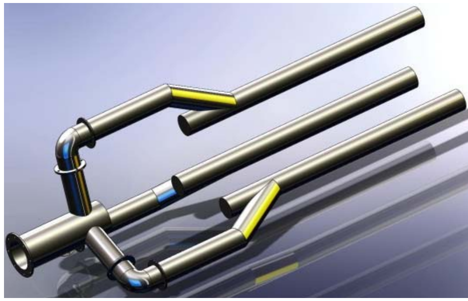




Advanced Fuels and Combustion Processes for Propulsion

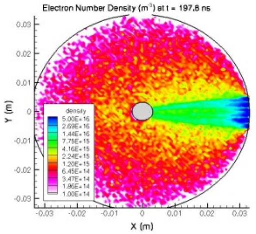
Office of Naval Research GLOBAL Science & Technology

USN



Gabriel D. Roy

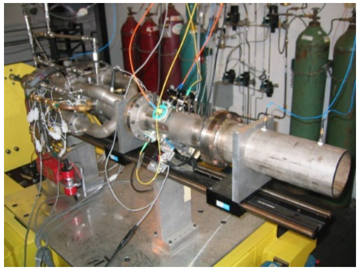
Office of Naval Research Global-Singapore

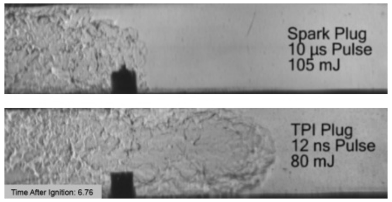


Fourth Indo-US Science and Technology Round Table Meeting

Bangalore, India

21-23 September 2010





Report Documentation Page

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14. ABSTRACT

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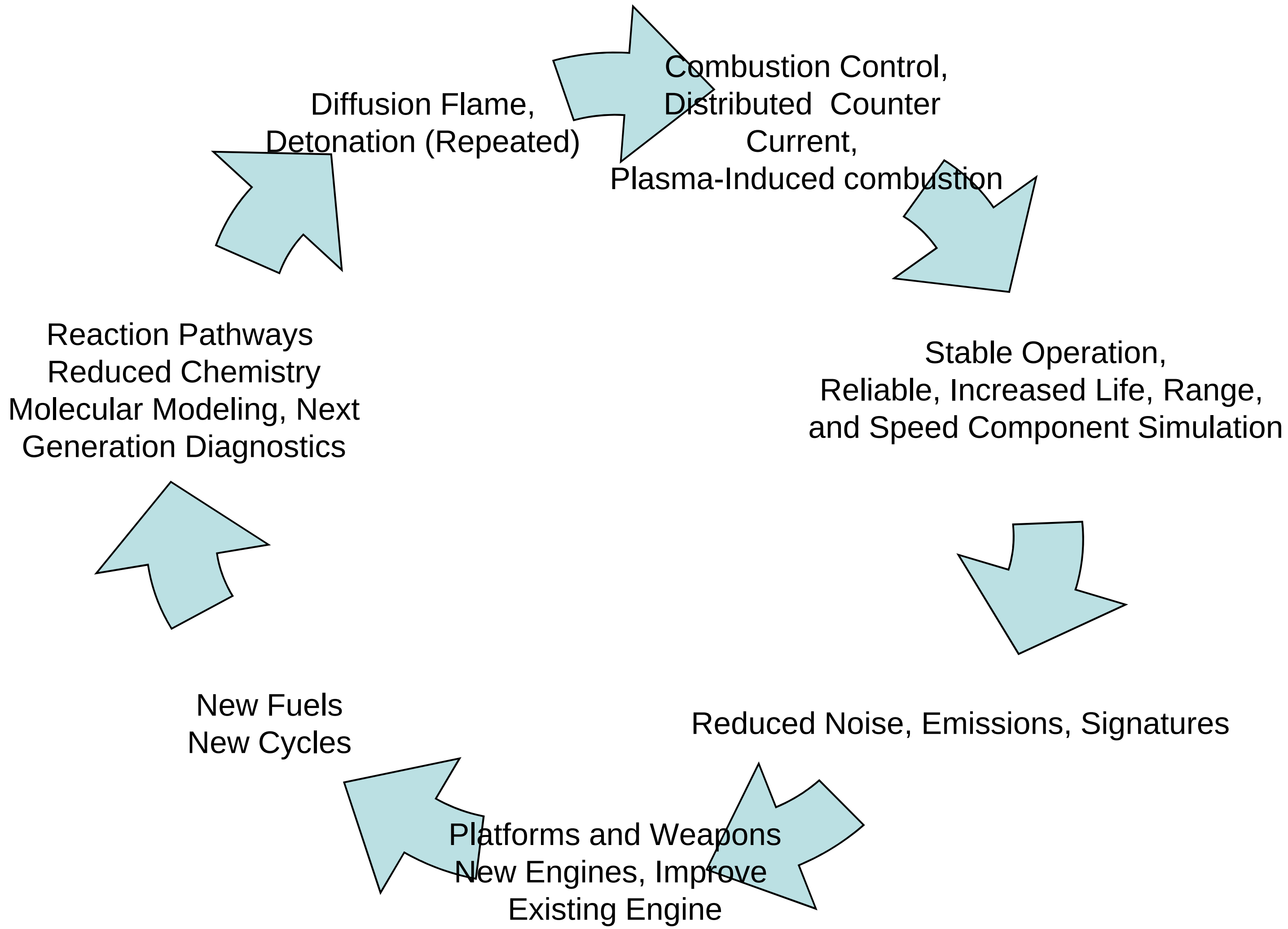
Why and How?

- Program goals:
  - Longer range
  - Increased speed
  - Reduced fuel consumption
  - Reduced cost of manufacture
  - Improve performance
  - Easier scaling

- Three avenues to achieve the goals:
  1. Improve combustion and propulsion efficiency by means of active control and other methodologies
  2. Increase the energy density of the fuel, so that for same fuel tank volume, increase in range, speed etc. can be achieved.
  3. Utilization of a more efficient thermodynamic cycle => Pulse Detonation Engines

Program Approach



Superior performance and environmental compliance at reduced cost.

G. Roy

Program Doctrine-A Combination of Science, Technology and Innovation

1. **Science - scholarship driven, passion for discovering and inventing.**
2. **Technology - market driven, knowledge of customer demand.**
3. **Innovation - competition driven, advantage over similar product.**

(1.2.3)

↓

Progress both technical and economic

Caution: 1 not leading to 2 - technology valley of death.
2 not leading to 3 - loosing to competition.

Evolution of a program in the right direction at level 1 is critical for future transition and success of the investments.

G. Roy

Program Strategy-A New Paradigm in Product Development

Programs initiated after consulting with Government, Academia and Industry via Work shops and Review Meetings (Utilize past research, identify issues, define approach, establish teams, International collaboration)

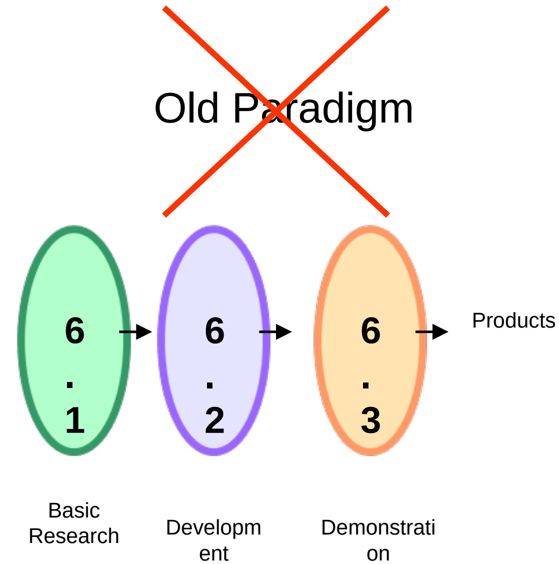
•Government, Academia, Industry Advisory Panel on Experts to Provide Critiques on Major accomplishments and future direction.

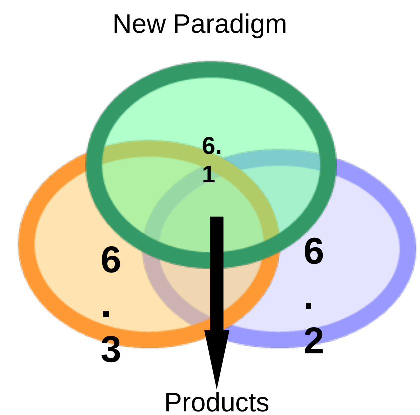
•Industry Participation in 3 Review Meetings Each Year (Annual Review and Two Mid-Year Reviews-Brain Storming)

•Encourage Faculty and Students to Participate in Industry Programs (eg. GE/Cal Tech, GE/UC, P&W/MIT)

•International collaboration (NICOP, Core)

•Wide Participation on National and International Technical Conferences.

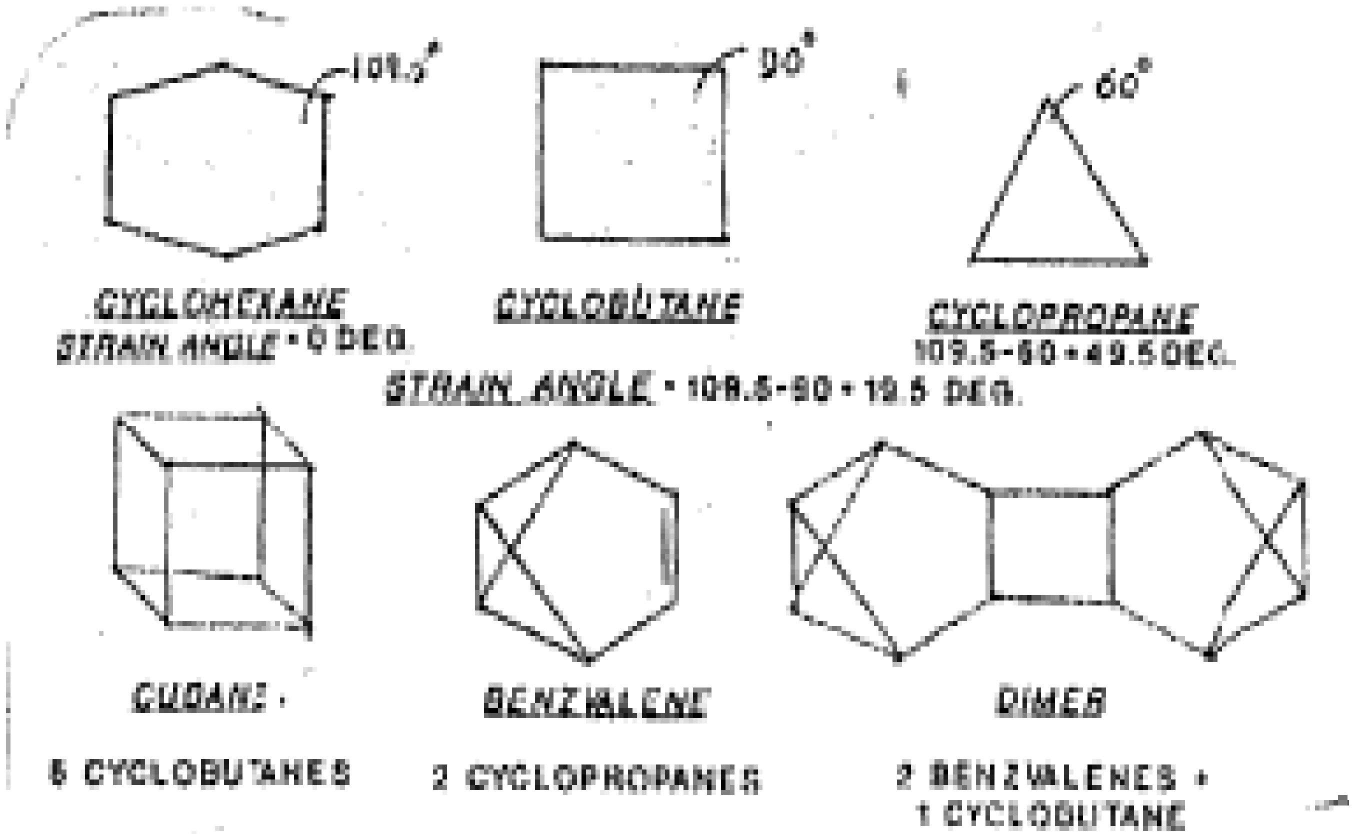




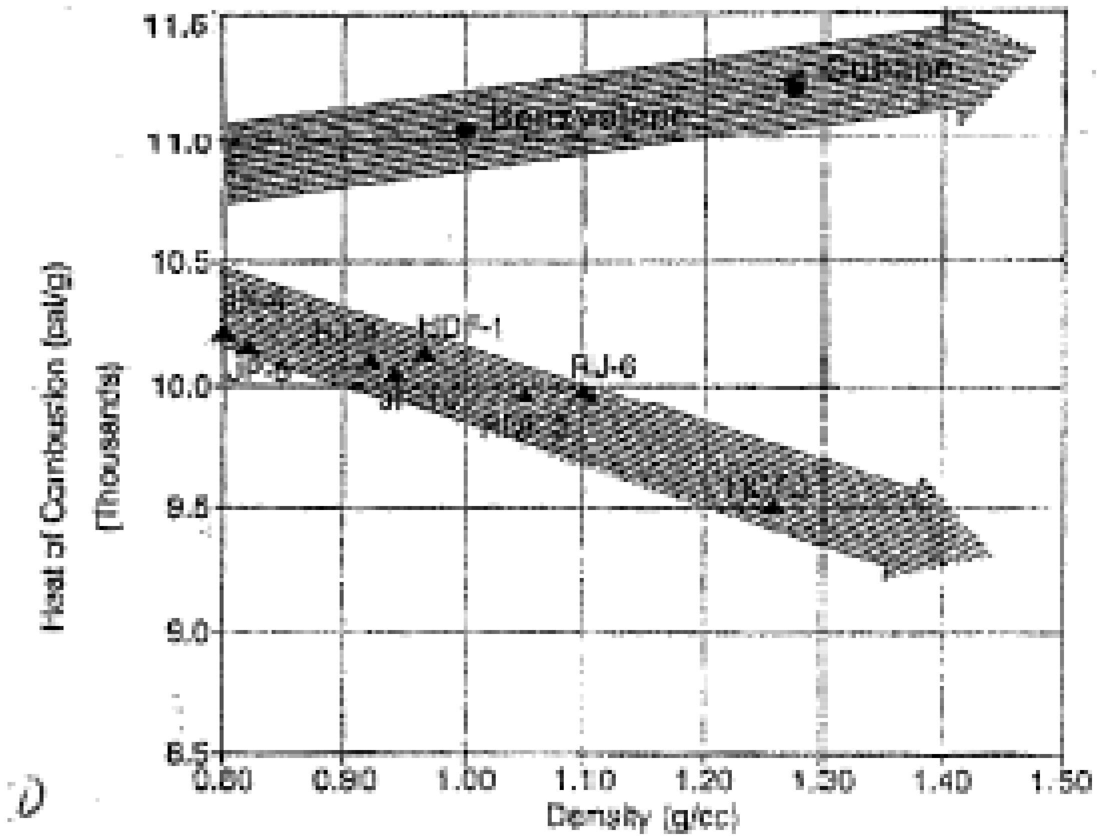
Originally presented At the ONR 1987 Program Review Meeting

Contents

High Energy Fuels



High Energy Fuels



Comparison of heat of combustion of various fuels

High Energy Fuels

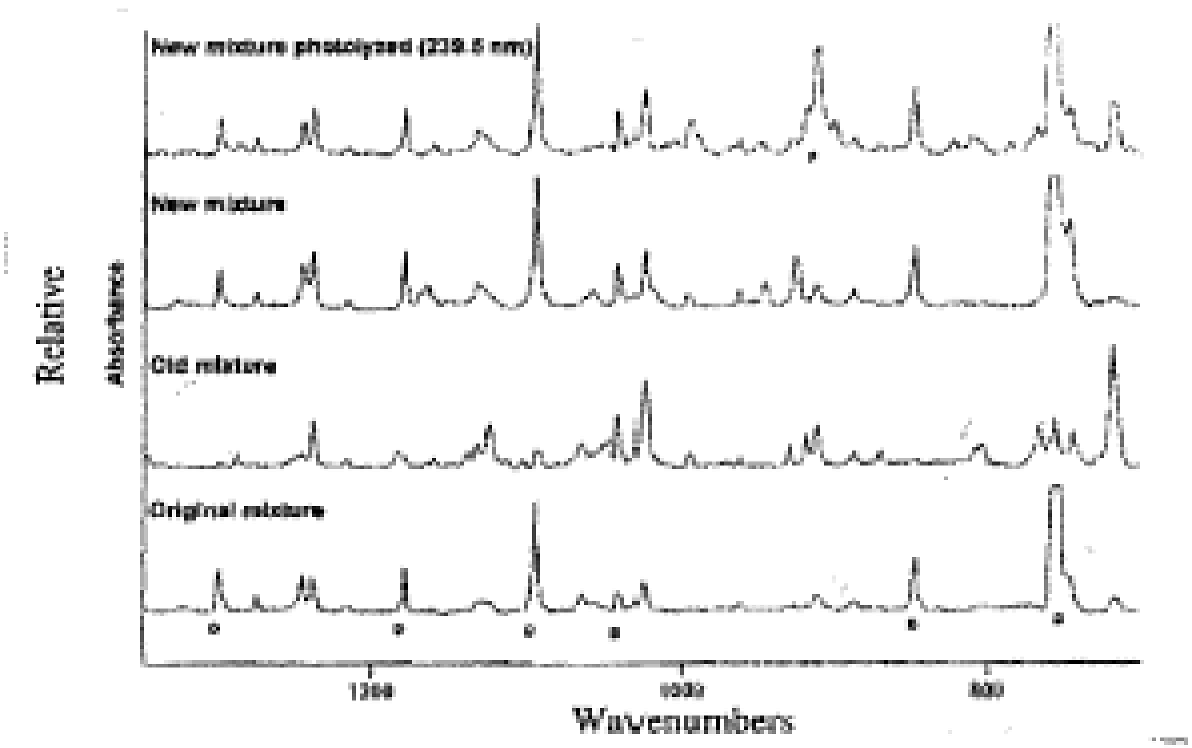
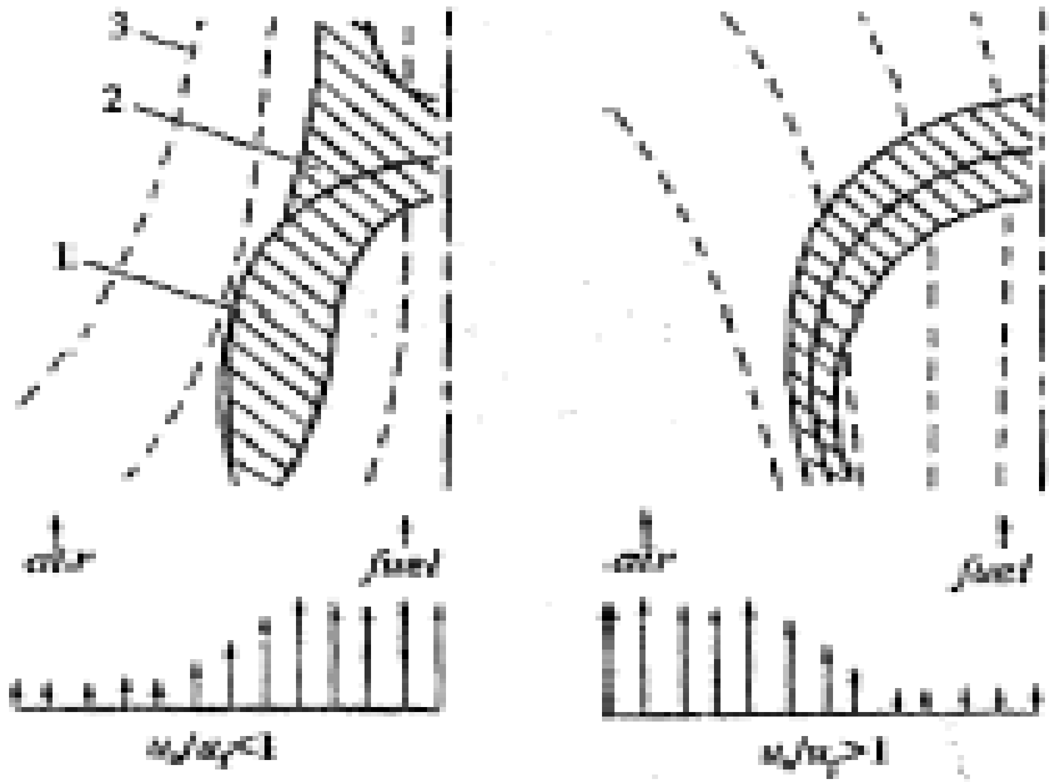


Fig. 4 Decomposition of DHBV during storage.

High Energy Fuels



Effect of reactant stream velocities on soot processes within laminar mixing layers for nonpremixed hydrocarbon-fueled flames. 1, flame sheet (typical); 2, soot layer (typical); 3, streamline (typical).

High Energy Fuels

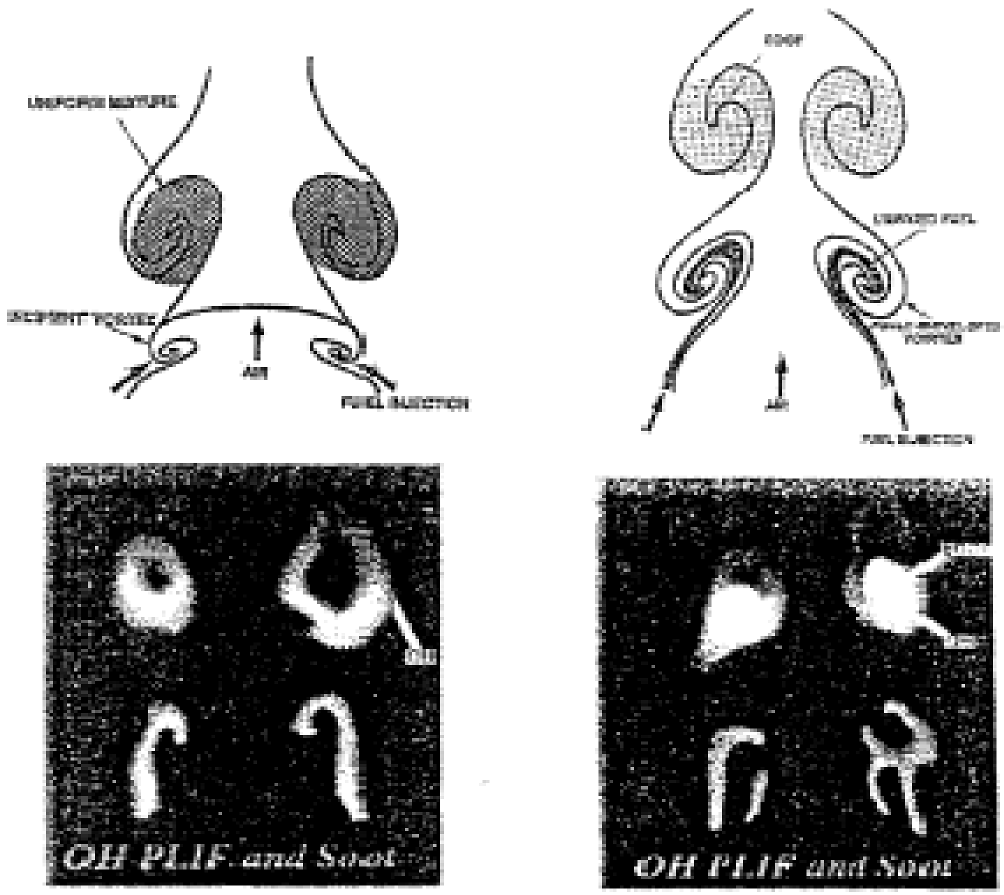
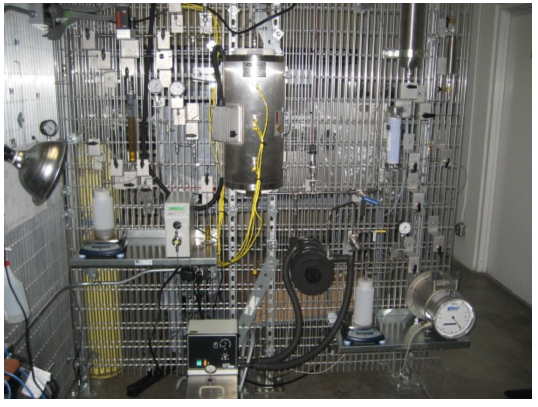


Fig. 8 Soot generation with and without controlled fuel injection.

Biojet Fuels from Non-edible Bio-oils and Cellulosic Biomass

Biofuel Pilot Plant



Feed & Product

- **Objectives**
  - Conduct tests to carry out decarboxylation of non-edible bio-oils
  - Conduct tests to demonstrate hydrogen enriched synthesis gas production from biomass steam reforming
  - Conduct a feasibility analysis of the proposed integrated process

- **Approach**
  - Decarboxylate a non-edible oil to produce a paraffin product. Hydroprocess the product to produce synthetic jet from biosources
  - Steam reform cellulosic biomass to produce hydrogen for decarboxylation and hydroprocessing
  - Build bench scale units to test decarboxylation of bio-oils and steam reforming of cellulosic biomass.

- **Pay-off**
  - Bio-jet production from renewable resources
  - Cost effective alternate supply of the logistic fuel for Navy
  - Indigenous source of fuel with less dependence on foreign oil.

Energia Technologies - D. Nguyen & K. Parimi
Florida State University - A. Krothapalli & B. Greska

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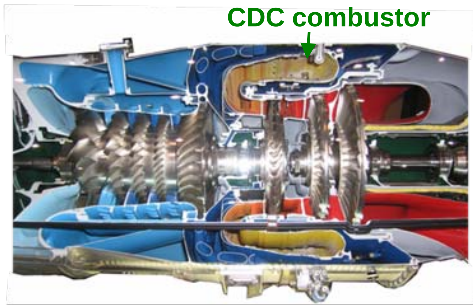
Development of Colorless Distributed Combustion (CDC) for Gas Turbine Engines

Diffusion Flame
NO=17ppm
CO=1310ppm

CDC Flame
NO=7ppm, 1 PPM [PM]
CO=12ppm, 35 PPM [PM]



Gas Turbine Engine

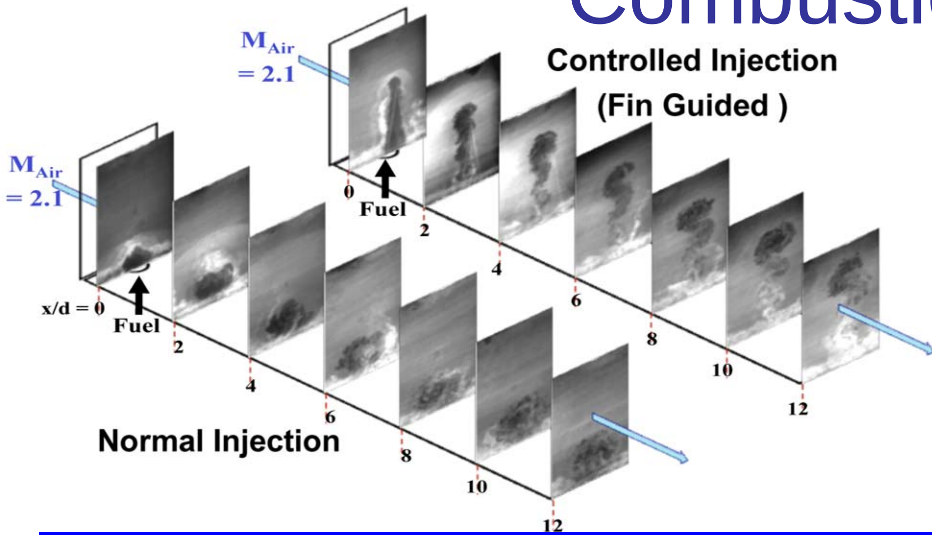
- **Objectives**
  - To examine feasibility of CDC at high thermal intensity (5→50MW/m^3-atm)
  - Examine the role of fuel/air mixing, gas recirculation and flowfield configurations on CDC
- **Approach**
  - Experimental: exhaust emissions, global imaging, acoustic signature, flow-field (PIV), thermal field
  - Numerical: flowfield (CFD), chemical kinetics, correlations

- **Project/Program Components**
  - Low Emission gas turbine combustor development with no visible flame color (colorless distributed combustion, CDC)
- **Pay-off**
  - Application of low emission CDC combustor for stationary gas-turbine engines for power generation
  - Low noise emission
  - Increased combustor and turbine life

- **Major Accomplishment**
  - Demonstration of low emission CDC flames for range of thermal intensity (5-40MW/m^3-atm)

A. K. Gupta and K. H. Yu
University of Maryland

Scramjet Fuel Injection, Mixing, and Combustion Control



- **Objectives**
  - Explore "fin-guided" fuel injection concept
  - Understand key physical mechanisms
  - Assess/optimize its effectiveness quantitatively
- **Approach**
  - Optimize mixing enhancement and pressure losses in non-reacting gaseous fuel injection
  - Extend the results to liquid fuel injection and supersonic combustion experiments

- **Pay-off**
  - Enable volumetrically efficient scramjet operation by reducing combustor length
  - Reduce specific fuel consumption by increasing combustion efficiency
  - Increase specific thrust by reducing pressure losses due to fuel injection shocks

◆ Major Accomplishment
- Scale-up experiments of supersonic mixing control were conducted in 6"x3" Mach 2 tunnel
- Planar Mie-scattering images and wall-pressure measurements showed:
  - Two-fold increase in fuel penetration height
  - 45% reduction in jet-induced shock strength

POC: K.Yu
Univ. of Maryland

PASSIVE CONTROL OF COMBUSTION NOISE FOR IMPROVED LIFE OF TURBINE ENGINES

- **Objectives**
  - Develop high-temperature porous material for passive control of combustion noise
- **Approach**
  - Ultra-High temperature and strength foam material development by Ultramet
  - Combustion experiments performed U. Of Alabama
  - End-user input provided by Solar Turbines

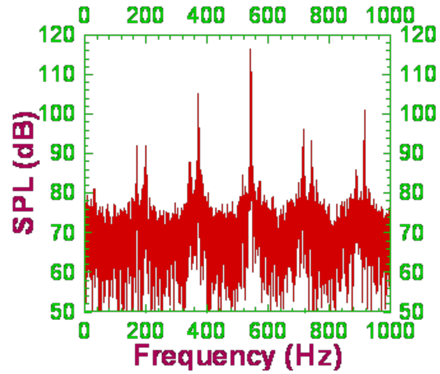
- **Pay-off**
  - Reduction in combustion noise in installations such as aircraft engines
  - Potential to eliminate combustion instabilities
  - Quieter and stable operation of stationary gas turbine engines

- **Major Accomplishment**
  - High-temperature HfC/SiC coatings have been developed, foam properties selected
  - Experiments have identified porous geometry parameters to minimize the combustion noise
  - Combustion instability is mitigated by our concept
  - High-pressure test facility has been developed

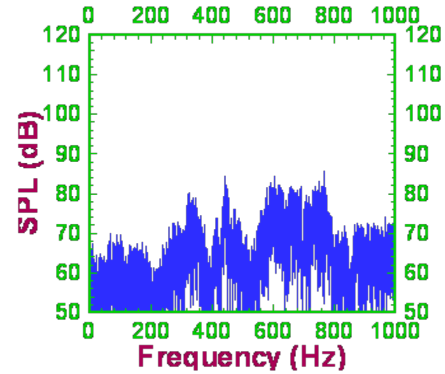
Name: Tim Stewart/Ajay Agrawal
Organization: Ultramet/University of Alabama

Accomplishments

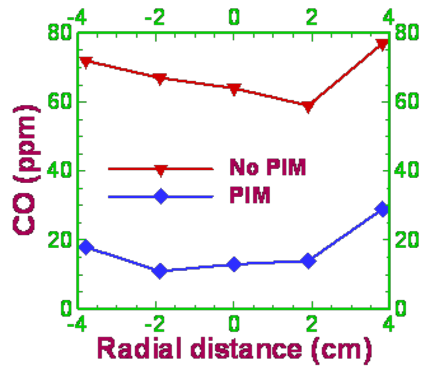
- Without the porous media, an increase in reactant flow rate increased noise which eventually led to combustion instability at a flow rate of about 600 slpm.
- With porous media, the combustion instability was suppressed, and the overall noise levels were significantly lower (up to 10 dB reduction).
- Emission measurements at these high reactant flow rates show a reduction in CO emissions but a slight increase in NOx emissions. Increased NOx emissions are likely caused by thermal feedback from porous media to produce locally high temperature zones in the present configuration.



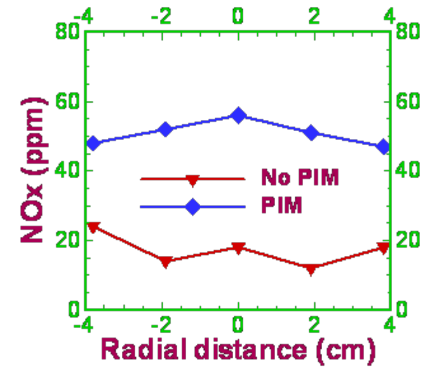
Noise Spectra without PIM
120.5 dB / 117.1 dBA
Combustion Instability



Noise Spectra with PIM
104.8 dB / 107.1 dBA
No Instability, 15 db reduction



Reduction in CO emissions With PIM



Increase in NOx emissions With PIM

Contents

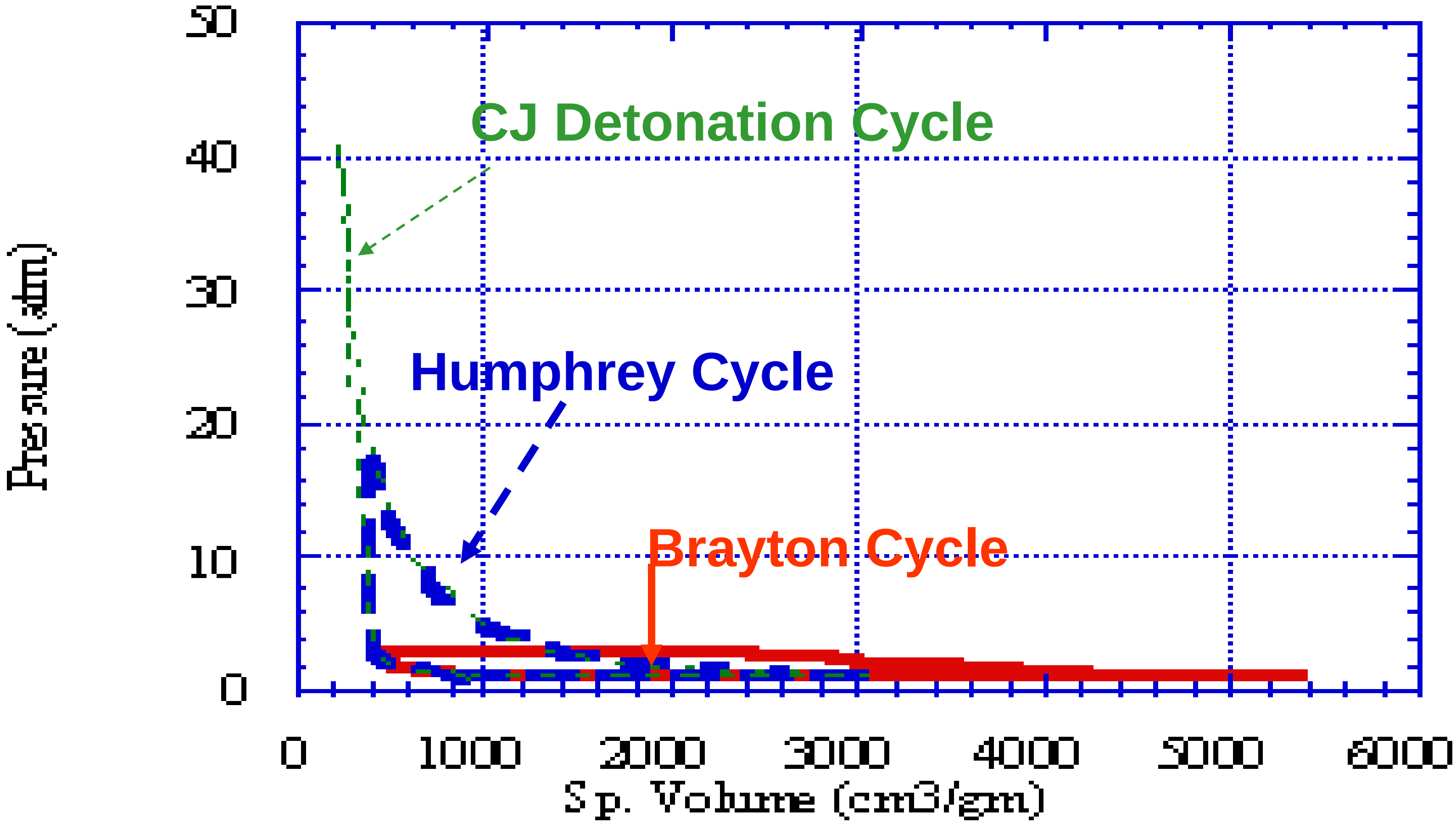
PDE Program Evolution

New concepts need systematic development

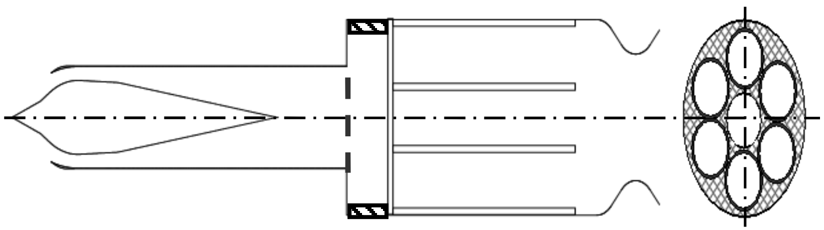
• July 1996	PDE concept discussed (by G. Roy) at the International Combustion Meeting in Naples, Italy
• Aug.1996	Half day workshop on PDE at the Propulsion Program Review Meeting
• Oct. 1997	Pulse detonation engine workshop at Naval Postgraduate School (70 attended)
• Jan. 1998	Initiation of core PDE program (modest funding)
• Sept. 1998	First International Colloquium on Detonation (Gaseous and Heterogeneous Detonation)
• 1999	PDE MURI approved (2 teams, Phase I-supplemental funding)
• July 2000	Second International Colloquium on Detonation (High Speed Deflagration and Detonations: Fundamentals and Control)
• May 2002	Core and MURI Phase II PDE programs
• July 2002	Third International Colloquium on Detonation (Confined Detonations and Pulse Detonation Engines)
• Dec. 2003	Plasma ignition demonstration
• July 2004	Fourth International Colloquium on Detonation (Pulse Detonation Applications)
• 2006	Integrated system demonstration with thrust measurement
• 2006	Fifth International Colloquium on Detonations
• 2008	Sixth International Colloquium on Pulse Detonation Engines and Devices
• 2010	Demo of multi-tube integrated system
• 2010	Seventh International Colloquium on Pulsed and Continuous Detonations

Pulse Detonation Engines

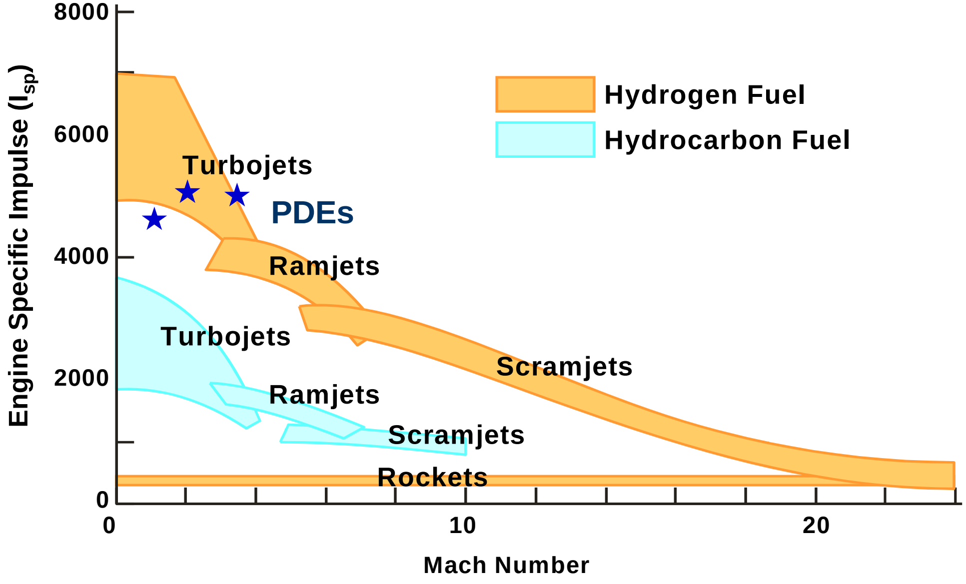
Comparison of Thermodynamic Efficiency of Various Cycles



Pulse Detonation Engines

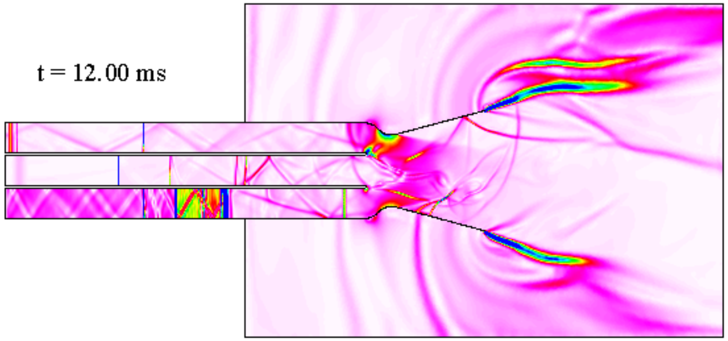


Characteristic performance by engine type



★ PDE Data: high-fidelity prediction based on full conservation laws with inclusion of all known effects

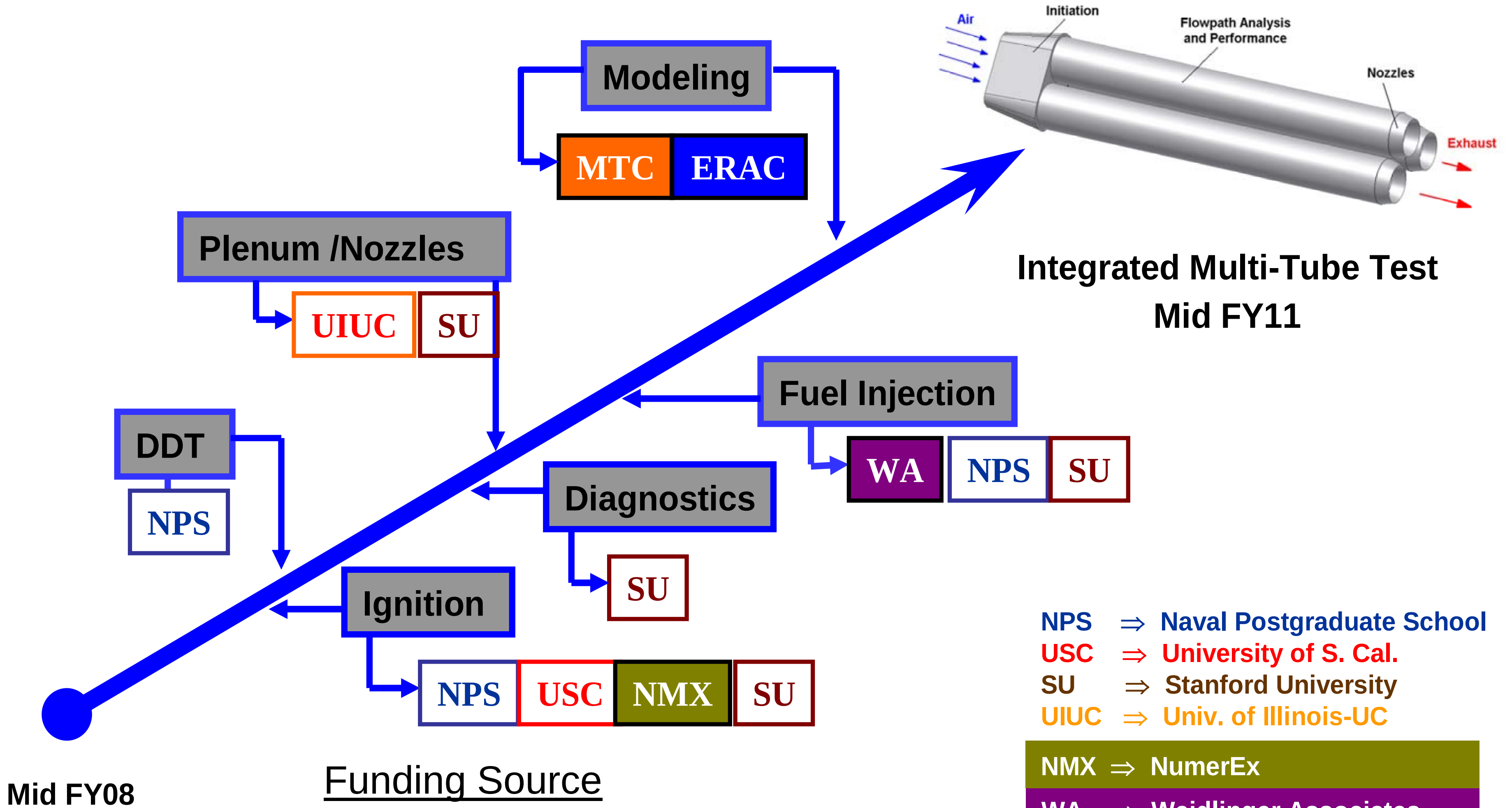
Typical density-gradient field in chamber



Advantages of PDEs

- High thermodynamic cycle efficiency
- High specific impulse (~20% > ramjet at M 2.1)
- Wide operation range & self aspiration
- Hardware simplicity
- Configuration scalability
- Low life-cycle cost

ONR Pulse Detonation Combustor Program Transition Roadmap



<u>Funding Source</u>

Core program, YIP, DURIP, etc.

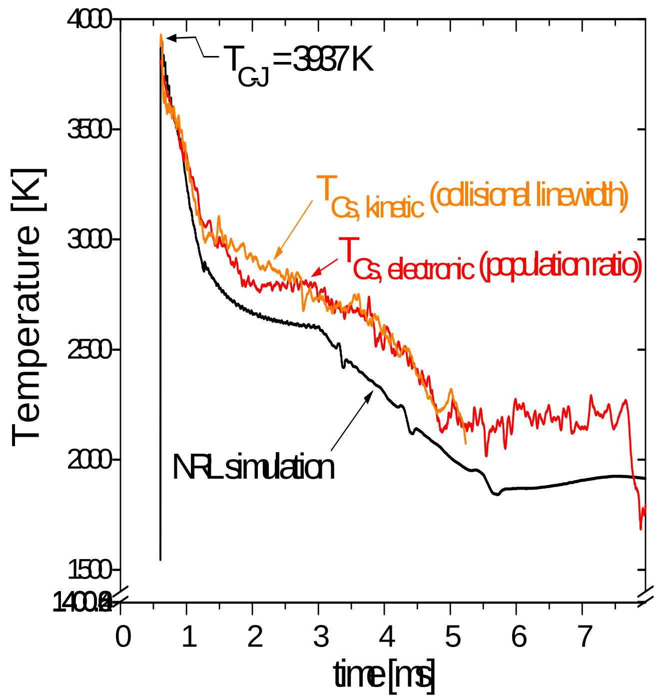
SBIR/STTR

NPS ⇒ Naval Postgraduate School
USC ⇒ University of S. Cal.
SU ⇒ Stanford University
UIUC ⇒ Univ. of Illinois-UC
NMX ⇒ NumerEx
WA ⇒ Weidlinger Associates
ERAC⇒ Eng. Research & Analysis.
MTC ⇒ Metacomp Tech.

Pulse Detonation Engine

Advanced Computations and Diagnostics Paved the Way for Detailed Study of Processes Involved.

Conventional Approaches	Innovative Approaches
1. DDT - Obstructions - Turbulence enhancers - Source: spark plugs 2. Direct Detonation Initiation - More powerful energy source - Reduction in system efficiency	1. Direct Detonation Initiation - Duel fuel (multi-fuel) operation - Fuel preprocessing - Plasma discharge ignition - Distributed energy deposition - Successive reactive shocks - Flame jet initiation - ***Hybrid approach***



Measured and Computed Gas Temperatures for Detonation of Stoichiometric C_2H_4 / O_2

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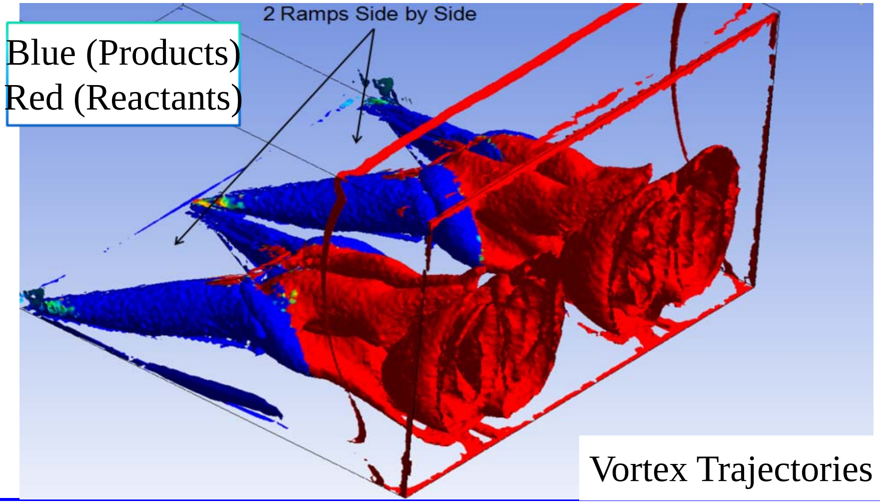
Operational And Performance Benefits Of Swept-Ramp Obstacle Configurations for PDC Systems



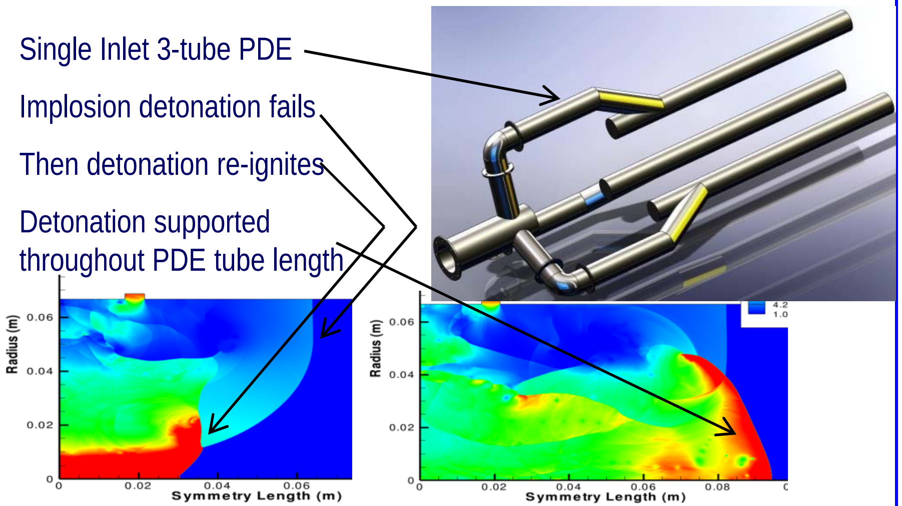
- **Objectives**
  - Develop low-loss detonation initiation approaches for PDC systems.
- **Approach**
  - Computationally model flow fields of favorable geometries.
  - Evaluate impact of new obstacles on thrust performance.

- **Pay-off**
  - Improved fuel efficiency.
  - Increased practicality of detonation formation translates into higher thrust values or higher shaft work availability for power generation. Applications include stand-alone and hybrid engines for stationary power, aircrafts and space transport

◆ Major Accomplishments
  - Significant reduction of total pressure loss associated with DDT obstacles(factor of 4)
  - New Swept-Ramp designs are substantially more reliable and more easily integrated into combustor fabrication.

Christopher Brophy
Naval Postgraduate School

Status Of 3-Tube PDE Designs and Advances In PDE Implosion Concepts



- **Objectives**
  - Investigate flow field in single inlet PDE designs for multiple tube applications
  - Investigate implosion techniques for specific thrust increases in PDEs
- **Approach**
  - Perform high-fidelity reactive CFD simulations to study above phenomena

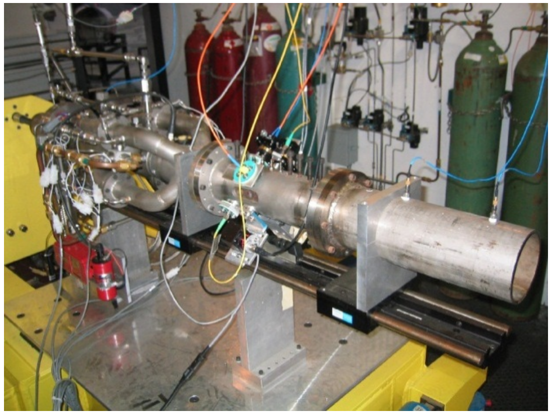
- **Pay-off**
  - By reducing complexity of a field-cable PDE system reduces costs, and total system weight and size, thus increasing reliability, operating envelope and range.
  - Simplify multi-tube PDE systems by transitioning to a single inlet design

◆ Major Accomplishments
  - Optimum single inlet dump angle and fuel injector location have been determined
  - Proof-of-concept for implosion technique has been demonstrated in CFD simulations

Prof. Jose O. Sinibaldi
Department of Physics
Naval Postgraduate School

Laser-Based Sensors for PDEs

Fiber-coupled laser sensor on NPS PDE



- **Objectives**
  - Establish *in situ* diagnostics to monitor PDE performance (NPS and elsewhere)
  - Develop laser diagnostics for application to advanced propulsion
- **Approach**
  - Time-resolved diode laser absorption

- **Project/Program Components**
  - Sensor development at Stanford
  - Field measurements at ground test facilities
- **Pay-off**
  - Diode laser absorption allows real-time monitor of combustion products (H_2O and CO_2), gas temperature, velocity and hydrocarbon fuel
  - Potential for time-resolved (needed for pulsed engines) measurements of enthalpy flux
  - New diagnostics paradigm for jet noise research

Major Accomplishments

1. Collaboration enabled first-time operation of NPS engine on JP-10/air via time-resolved fuel loading
2. First application of fiber-coupled mid-IR absorption sensing to propulsion diagnostics
3. Sensor provides simultaneous time-resolved temperature measurement
4. First application of the fluctuations of time-resolved absorption to characterize jet noise

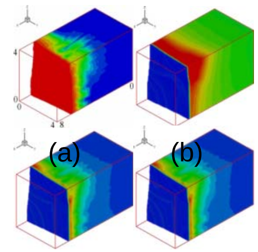
R.K. Hanson (PI), Stanford University

The Optimal Detonation Transition Length From a Small Pre-Detonation Chamber to a Main Detonation Chamber of a Pulse Detonation Engine

Objectives

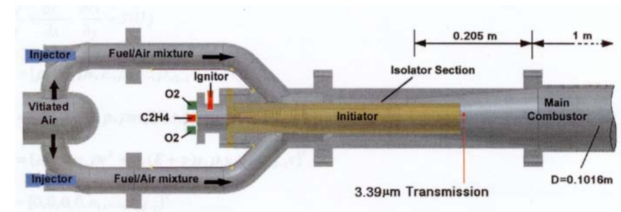
Long Term Goals: Characterize the physics of DDT and aid in the determination of structural geometries needed for optimal DDT to design scalable, smaller, lighter and more reliable Pulse Detonation Engines (PDEs).

Objective(s): 1. Use of 3-D Model to understand the underlying mechanism for detonation sustenance as the geometry of the tube changes in dimension in the downstream direction. 2. Model the 3-D DDT for various geometries including the multi-ramped geometries being tested at Naval Post Graduate School. 3. Validate models on NPS prototype.



(c) (d)

Contours of the flow and reaction variables at 60,000 time steps for the narrow duct at dimensionless time t = *22.26. The* parameters for the reaction are $q = 50$, $Ti = 20$, $\gamma = 1.2$, *and* $f = 1.0$. *(a) Mass fraction of reactant; (b) pressure; (c) density;* (d) streamwise velocity.



Participants

National University of Singapore:

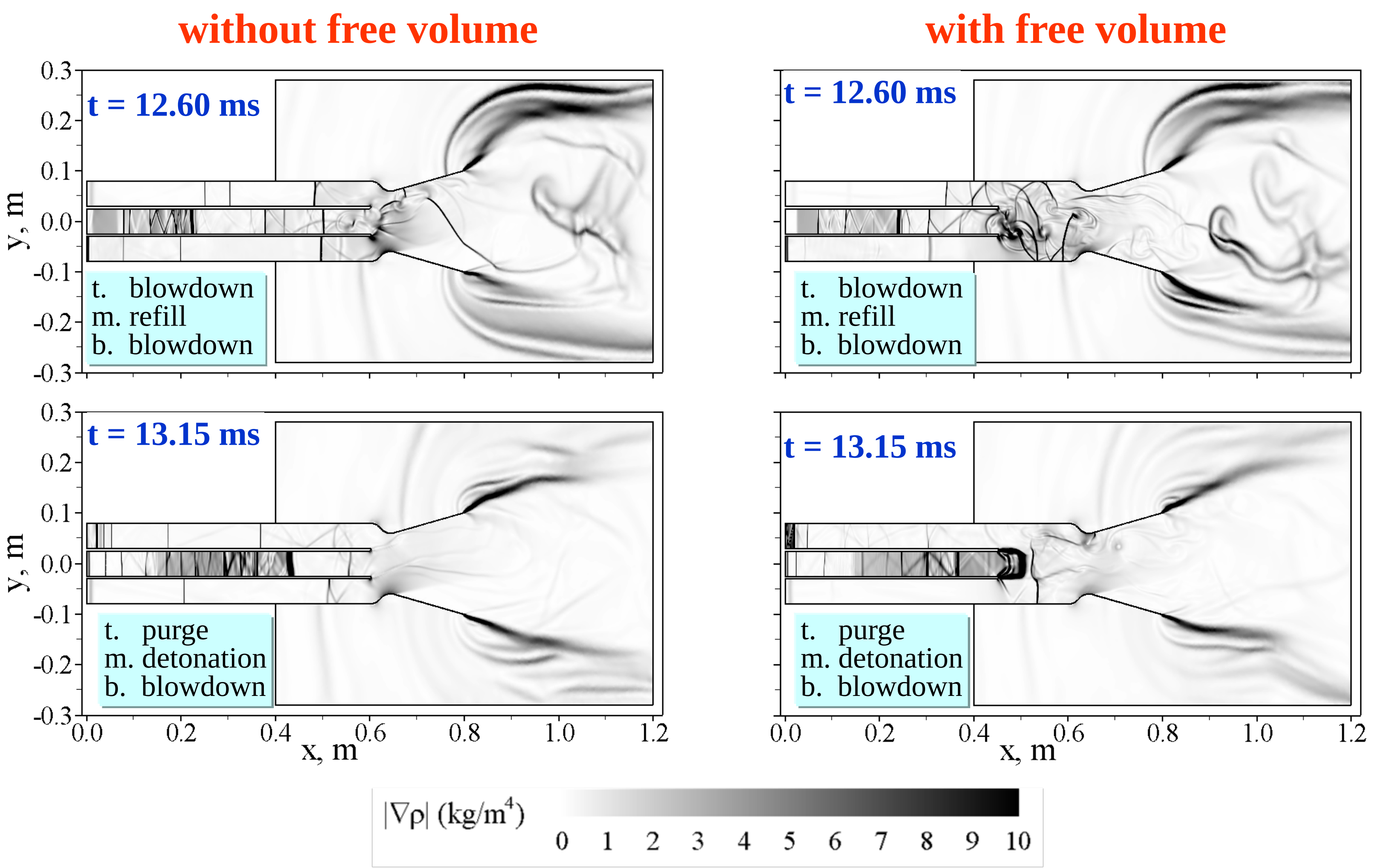
Dr. Boo-Cheong (BC) Khoo

Naval Post Graduate School:

Dr. Christopher Brophy, Dr. Jose Sinibaldi

Pulse Detonation Engines

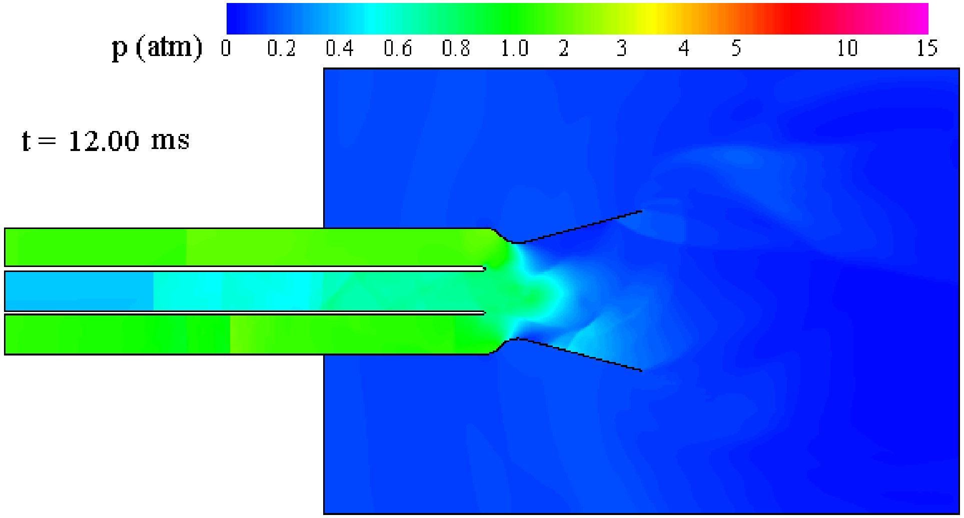
Pressure Velocity



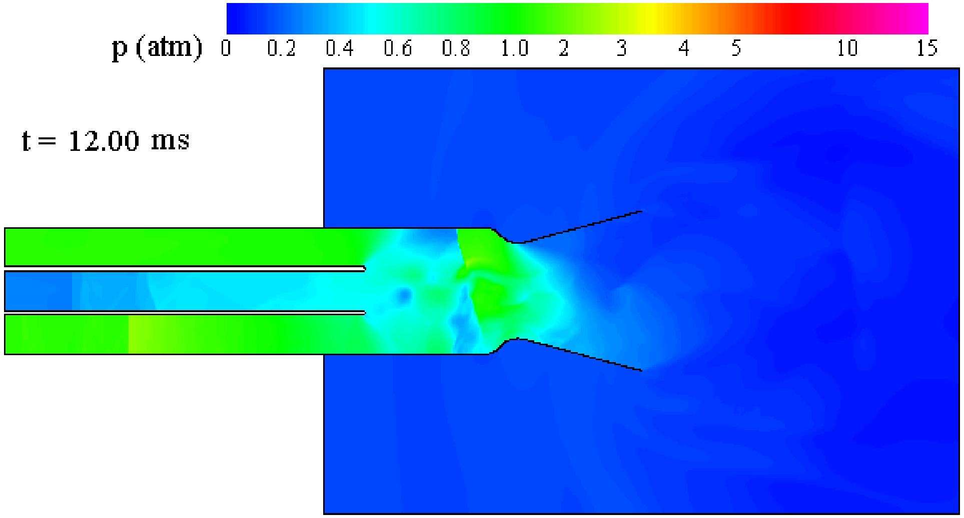
Pulse Detonation Engines

Pressure Velocity

without
free volume



with
free volume

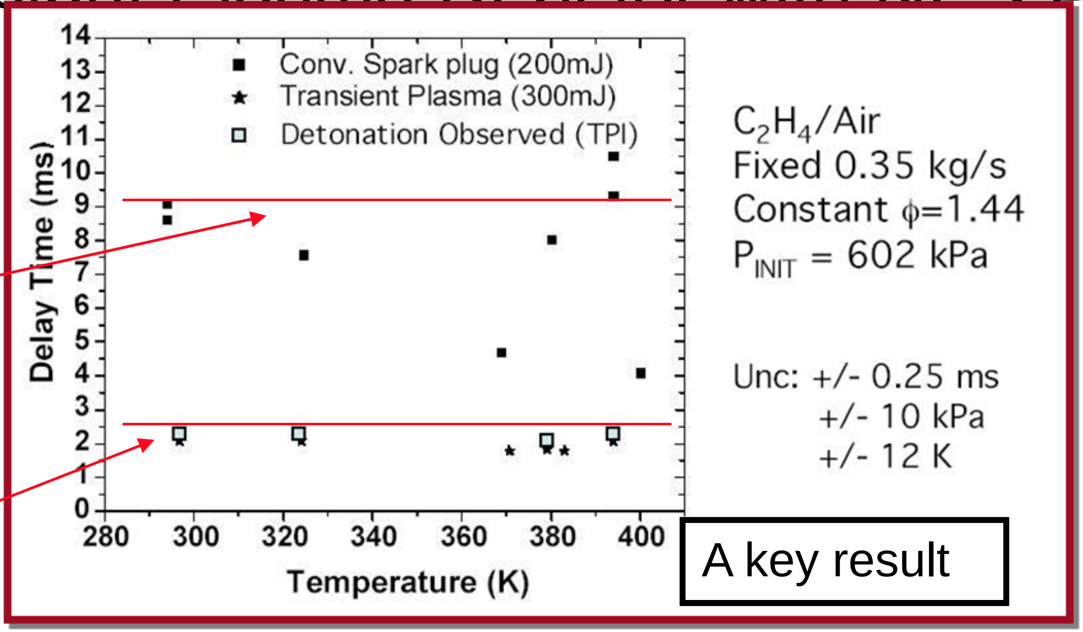


hydrogen/air
$\Phi = 1$
$p_\infty = 0.29$ atm
$T_\infty = 228$ K
$\tau_{cycle} = 3.0$ ms
$\tau_{close} = 2.1$ ms
$\tau_{purge} = 0.1$ ms

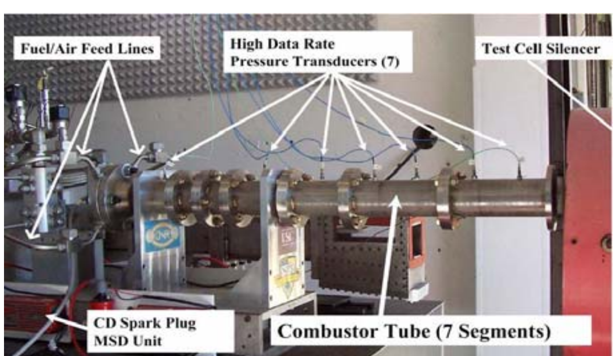
Pulse Detonation Engines

Transient Plasma Reactor with NPS PDE

Traditional Arc ignition
9 ms delay



USC
Transient plasma ignition
2 ms delay



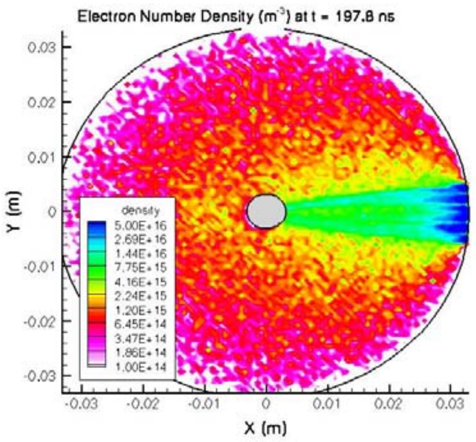
With transient plasma we

- Considerably shortened the peaking time
- Created a detonation without added oxygen (propane-air)
- Improved the DDT time and increased the peak pressure
- ***Enabled higher repetition rate operation of the PDE***

High flow rates (1/3 kg/sec)

Shortened DDT by factors >4 (9 to 2 msec)

Transient Plasma Ignition for High Repetition Rate Pulse Detonation Engines



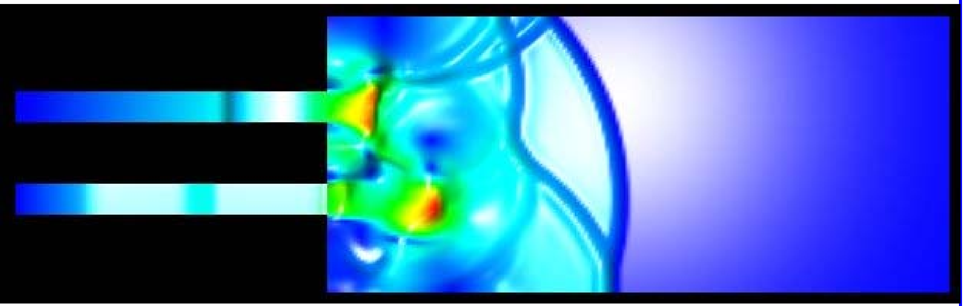
- **Objectives**
  - Development of next-generation ignition system for high rep-rate pulsed detonation engines
- **Approach**
  - Exploitation of transient plasma ignition via a combination of theory, computation, and experiment

- **Project/Program Components**
  - Support of Novel Pulsed Detonation Engines
- **Navy Relevance (Pay-off)**
  - Development of advanced, air-breathing propulsion technology that will be exploitable for rapid strike (from Mach 0 to Mach 4) scenarios

- Major Accomplishments
  - Experimental measurement of OH and ozone sensitivity to $H_2 0$, agreement with chemistry calculations
  - Identification of candidate mechanisms that influence detonation rep rate
  - Initiated multidimensional streamer modeling

Jack Watrous
NumerEx

Pulse Detonation Engine Cycle Performance Prediction Code



- **Objectives**
  - Simulation of multi-cycle operation of single and multi-tube PDEs
- **Approach**
  - Time resolved Q1D simulation of single tube PDEs with inlet and nozzle
  - Blending Q1D with multi-dimensional description for multi-tube PDEs with common nozzle

- **Project/Program Components**
  - Single tube multi-cycle PDE analysis capability
  - Inlet valve controls
  - Multi-tube multi-cycle PDE analysis capability

- Major Accomplishments
  - Multi-cycle simulation capability
  - Inlet valve controls
  - Impact of operating frequency on performance
  - Multi-tube, common nozzle PDE infrastructure

Metacomp Technologies

Piezoelectric Single Crystal for Improved Fuel Injector Application

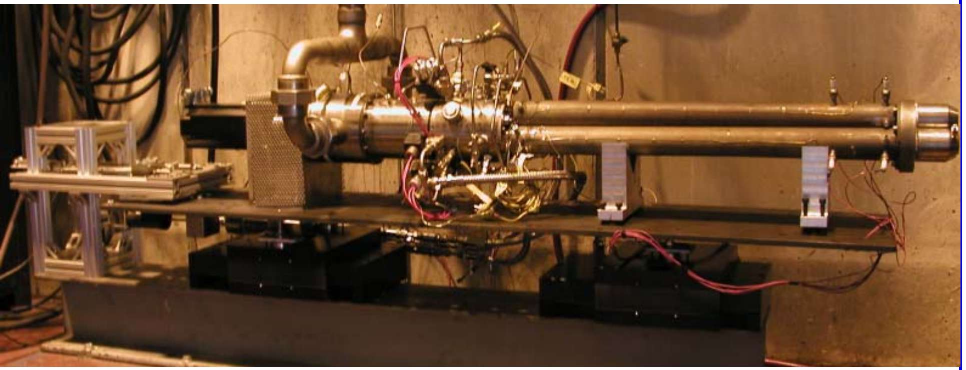
- **Objectives**
  - Develop piezoelectrically actuated fuel injectors for Pulse Detonation Engines.

- **Pay-off**
  - Will provide appropriate fuel:air mixture in time and space for PDEs. Also will aim to provide improved power, efficiency and emissions for regular combustion engines.

- Major Accomplishments
  - Actuator stacks designed and manufactured
  - Drive and amplification electronics
  - Injector housing designed and manufactured

Paul Reynolds
Weidlinger
Associates

Pulse Detonation Engine Cycle Testing: Performance Perdition Code, PDE++



- **Objectives**
  - Validation of performance estimations of a single tube and a multitube PDE
- **Approach**
  - Use open literature to semi-validate PDE++ performance estimations
  - Use GRC 3-tube test data measurements of thrust and pressure-time traces to validate PDE++

- **Project/Program Components**
  1. Tested LINUX version on site
  2. Tested Windows version on site
  3. Developed a translator to estimate thrust and I_{spf}
  4. Semi-validate with estimations in the literature..Ongoing
  5. Validate using test measurements of thrust and P-t traces…Ongoing

◆ Major Accomplishments
- 1.5 minutes of wall time per cycle
- Semi validations show
- Impact of operating frequency on performance
- Multi-tube, common nozzle PDE infrastructure

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3. **Gaseous and Heterogeneous Detonations: Science to Applications:** Ed. G. Roy, S. Frolov, N. Smirnov, K. Kailasanath. *ENAS*, 1999.
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6. **Detonations and High Speed Deflagrations: Fundamentals and Control:** Ed. G. Roy, S. Frolov, D. Netzer, A. Borisov. *Elex-KM Publishers*, 2001.
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8. **Confined Detonations and Pulse Detonation Engines**: Ed. G. Roy, S. Frolov, R. Santoro, S. Tsyganov. *Torus Press*, 2003.
9. **Application of Detonation to Propulsion,** Ed. G. Roy, S. Frolov, J. Shepherd. *Torus Press*, 2004.
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11. **Pulse and Continuous Detonation Propulsion. Ed. G. Roy, S. Frolov,** *Torus Press*, 2006.
12. **Pulse Detonation Propulsion: Challenges, Current Status and Future Perspective.** G.D. Roy, S.M. Frolov, AA Borisov, D.W. Netzer. Program in Energy and Combustion Science, Elsevier 2004.

Contents

Major Issues Addressed and To Be Addressed

- Addressed
  - Detonation Initiation
  - Detonation Repetition
  - Detonation Diagnostics
  - Control of Detonation Flows
  - Predictive Tools
  - System Analysis
- To Be Addressed
  - Tailored Fuels
    - High Energy Density
    - Easily Detonable
  - Noise
    - High Peak Noise Levels
    - Repetitive Noise
    - Acoustic Wave Interaction

Material Issues

- Changes in Frequency of Firing
- Order of Firing in Detonation Chambers
- High Speed Flows
- Wall Cooling
- Environmental Effects
- High Heat Release
- Fatigue (Mechanical and Thermal)
- Crack Propagation

Contents

- Introduction
- Advanced Fuels
- Combustion Control
- PDE Program Evolution
- Program Status
- Major Issues
- Conclusion

Conclusions

In order to meet the requirements of future propulsion systems. Three scenarios- advanced energetic fuels, improved propulsion process, and more efficient thermodynamic cycles- are to be addressed.

- High energy strained hydrocarbon fuels such as methyl cubanes, benzvalenes etc. have been synthesized and characterized. Large scale production have not been achieved yet.
- Advanced combustion processes including passive and active control of combustion, flameless oxidation/combustion, utilization of porous inserts etc. have been researched and developed.
- More efficient thermodynamics cycles such as Humphrey Cycle are addressed-pulse detonation engines, and continuous wave detonation engines are being developed.
- PDE has been a major focus of the ONR propulsion program.

Conclusions

- ONR has funded probably the most extensive and thorough Pulse Detonation Engine related research.
- The program initially focused on understanding the phenomenon of repeated (pulse) detonation for propulsion application.
- With the help of various funding resources, research addressed fuels, component development and CFD based tools for component design and optimization, flow analysis, predictive models and system studies.
- International Colloquia sponsored by ONR provided access to decades of fundamental research done abroad, and helped industry benefit from both literature and personnel.
- Multiple application possibilities emerged from the findings of the research.
- Close collaborations with industry and timely review meeting allowed speedy transmittal of scientific research to the development community.
- The understanding acquired from the program provided a basis for solving further issues such as noise, fatigue, and the development of tailor-made fuels and materials to meet the challenges.

Conclusion

Detonations…..

If detonation is our present quest's ultimate destination,
I may say, with some confidence, we have seen the horizon.
But if detonations are to drive a new generation of engines,
I have indeed miles and miles of water to sail across.

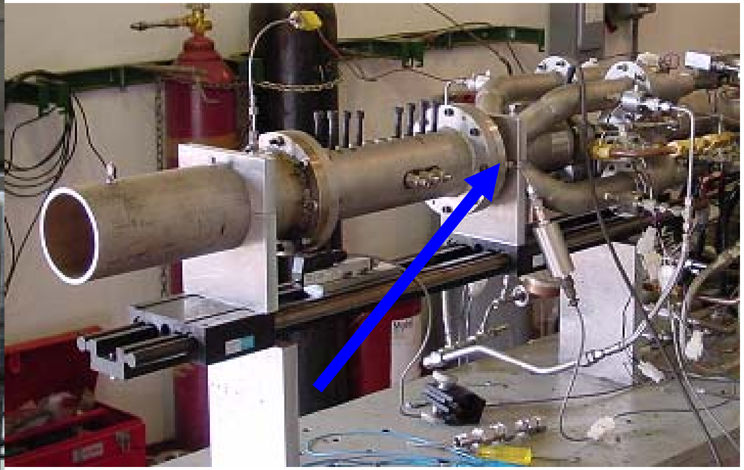
But the deep water seems to be calmer than I envisioned;
Yes, the tides are high and unpredictable, but I am not afraid.
The best sailors, trained in turbulent waters, are on board;
Yet, I look for more to help me further along the road.

Detonation is a new frontier to me, but I have the will to steer,
And if you have the willingness, strength and desire-
Together we can conquer, capture and control this frontier,
And look above to see detonation-driven engines flying in the air!

G. Roy

Pulse Detonation Engines

The PDE Crew at NPS



Ignitor